ARE MASSIVE HALOS BARYONIC?

Dennis J. Hegyi

Department of Physics
University of Michigan
Ann Arbor, Michigan

ABSTRACT

The problems with massive halos being composed of baryonic matter are discussed. Specifically, a halo composed of either gas, snowballs, dust and rocks, low mass stars, Jupiters, dead stars or neutron stars is shown to be unlikely. Halos could be composed of black holes less than 100 M_0 if they, unlike the stars in this mass range, are extremely efficiently accreting or primordial. At present, however, particles from supersymmetric theories appear to offer the most interesting possibilities as the constituents of halos.

I. INTRODUCTION

Spiral galaxies are surrounded by halos, large amounts of sub-luminous or non-luminous matter. These halos are approximately spherical in shape and may extend out to distances as far as ten times the optical radius of a spiral galaxy.

The supporting evidence for halos is quite compelling. Using dynamical arguments based on the rotation curves of spiral galaxies, it is possible to accurately determine the halo mass as a function of galactic radius. Also, a number of independent arguments require that halos be approximately spherical. Based on the information available about halos, it is not difficult to show that halos contain about 10-100 times the mass in the disks of spiral galaxies, and consequently, contain a significant fraction of the cosmological mass density.

J. Audouze and J. Tran Thanh Van (eds.),

In contrast to the definite statements that can be made regarding the existence of halos, very little can be said about the exact nature of the halo mass. At present, it appears that the most direct way to determine the composition of the halo mass is to show what halos cannot contain.

In the present investigation we argue that halos are not composed of baryons. Our approach will be to show the problems associated with the following types of baryonic matter: gas, snowballs, dust and rocks, Jupiter-like objects, low mass stars, dead stars and neutron stars. It appears very difficult to avoid the problems that we shall present if halos are baryonic. We shall discuss a model in which it is claimed, a primordial halo composed of gas can be converted into Jupiters, and show that it is not self-consistent.

Though not baryonic, black holes are a possible constituent of halos. If halos are composed of black holes they must be extremely efficiently accreting or primordial. Aside from the possibility of efficiently accreting black holes, we expect the cosmological baryonic abundance to be low at the time of nucleosynthesis. We shall briefly discuss the current situation regarding the observed nuclear abundances in terms of cosmological production in a low baryon density universe.

One of the earliest discussions of massive halos surrounding spiral galaxies was given by Hohl (1,2). He found his models of spiral disks to be unstable with respect to the growth of long wavelength modes, and as a result, the disks tended to develop into bar-shaped structures within about two revolutions. Hohl was able to stabilize his models by adding a fixed central force which he identified with a halo population of stars and the central core of the galaxy. Kalnajs (3), considering only exact solutions for infinitely thin spiral disks, explored ways of stabilizing the initially cool rotational state. Perhaps his most interesting result was that by embedding the spiral disk in a uniform density halo, stability could be obtained.

The possibility that spiral galaxies might be surrounded by massive halos was emphasized by Ostriker and Peebles (4). Using a 300-star galactic model they studied the instability of spiral structure to the development of bar-like modes. The onset of instability was reached when t, the ratio of the kinetic energy of rotation to the total gravitational energy, increased to a value ~0.14. From a literature survey, the authors concluded that for systems ranging from fluid MacLaurin spheroids to flat galactic systems with 10^5 stars, the critical value for the onset of instability appears to be $t \approx 0.14$. Two different ways were suggested to stabilize the spiral structure, a hot disk population with radial orbits and a hot spherical halo. From a variety of arguments, it is now known that the halo mass distribution is spherical.

The strongest observational evidence supporting the existence of massive halos is dynamical. The rotation curve of a galaxy must satisfy the criterion that in equilibrium the inwardly directed gravitational force must balance the outwardly directed centrifugal force. Rotation curves of galaxies have been obtained by both optical and radio techniques (5-11). Data obtained on more than 50 spiral galaxies reveal symmetric rotation curves which support the equilibrium condition

$$M_r = \frac{K}{G} v^2 r \quad . \tag{1}$$

where M_r is the mass within radius r, K is a constant ranging from $2/\pi$ for a thin disk to unity for a spherically symmetric mass distribution, G is the gravitational constant, and v is the circular rotational velocity at galactic radius r. The observations show that v is a constant independent of r, and, as may be seen from eq. (1), $M_r \propto r$.

Beyond about 50 Kpc it is difficult, typically, to observe rotation curves, and binary galaxies (12,13) have been used to sample the halo mass distribution at large radii. Unfortunately there are a variety of selection effects which binary galaxies are subject to and it has not yet been possible to untangle these effects sufficiently to unambiguously interpret the results (14).

As already mentioned, several arguments have been used to show that the mass distribution of halos is spherically symmetric. The persistence of warps in spiral disks (15,16), star counts (17), and the scale height of stars perpendicular to spiral disks (18,19), all indicate relatively spherical halos, i.e. with aspect ratios close to unity.

II. EVIDENCE AGAINST NONBARYONIC HALOS

Much of the discussion about nonbaryonic halos has been presented elsewhere by Hegyi and Olive (20). Here we shall summarize parts of that discussion and amplify other parts. Before starting, however, we define a "standard halo" which we shall need to evaluate a variety of properties of baryonic halos. For this halo, $M_r \approx 10^{12}\ M_\odot$ in a radius of 100 kpc.

First we consider a halo made of gas. In a cold gaseous halo, particles moving on radial orbits would quickly collide with other gas particles and collapse on a gravitational timescale $\tau_c = (3\pi/32G\rho)^{1/2} \approx 5\times10^8$ yrs. Since halos must persist for 10^{10} years, they must be in hydrostatic equilibrium and they must be hot. Our standard halo, if it were gaseous, requires an equilibrium temperature of $T_{EQ} \approx 2\times10^6$°K which is sufficiently hot to violate the upper limits on the X-ray background by a factor of 20. The X-ray emissivity is sensitive to Ω_{Halo}, the fraction of the critical density contained in halo. We use $\Omega_{Halo} > 0.05$ (21).

A halo of snowballs will not be stable on a cosmological timescale. Snowballs, consisting primarily of hydrogen, are distinguishable from Jupiters because they are bound electrostatically. It turns out that the binding energy of a hydrogen molecule to solid hydrogen is sufficiently small so that it easily escapes, even when the temperature of the snowball is at 3°K, the temperature of the present cosmic background radiation. In fact, halos must have formed when the temperature of the cosmic background radiation was over 7°K; since halos are composed of non-interacting particles and cannot evolve to higher densities, they must have formed when the density of the universe had a density about equal to the present density of halos.

The argument against a halo of snowballs requires two steps. Based on laboratory measurements on solid hydrogen, its vapor pressure at 3°K has been found to be about 9×10^{-12} mm (22). This is high enough so that it is possible to show that there is no equilibrium between the solid and gaseous phase of hydrogen. The second part of the discussion involves the rate at which molecules evaporate to reach equilibrium. The time for evaporation (23) of a H_2 molecule (molecules rather than atomic hydrogen, will leave the snowball preferentially because their binding energy is lower) is

$$t_{ev} \sim [\nu_0 \, e^{-b/kT}]^{-1} \quad . \qquad (2)$$

The evaporation time is the inverse of the product of two terms: a Boltzmann factor which is the probability of a system attaining the escape energy, and an attempt frequency, the number of times per second that the system strikes the barrier. The reader is referred to (20) for more details. Here we report that at 3°K, the evaporation time per molecule is less than 10^{-8} seconds.

Next we consider a halo composed of dust and rocks, i.e. metals. A halo made of metals would contain a factor of about 50 times the mass of the disk of a spiral galaxy. The factor of 50 arises as the ratio of $\Omega_{Halo}/\Omega_{Disk} \gtrsim .05/.001 \simeq 50$. The problem is that if even a very small fraction of the halo mass mixed with the disk it would lead to a large metal abundance in the disk. Since the halo is believed to have formed before the disk and since there are disk stars with metal abundances $Z \sim 10^{-5}$, this implies that less than about one part in 5×10^6 of the halo mixed with the disk gas. It is difficult to believe that the halo could be composed of metals without contaminating the disk at such a low level.

The next possibility that we consider is a halo composed of low mass stars or Jupiters (24), that is, objects which are gravitationally bound with $m \lesssim 0.08\ M_\odot$ which do not have high enough central temperatures to support nuclear burning. By making observations of the surface brightness of the halo, it is possible to set limits on the mass in low mass stars. If a connection can be established between the nuclear burning stars ($M > 0.8M_\odot$) and the Jupiters, then by establishing constraints on the luminous portion of the initial mass function, constraints are simultaneously set on the non-nuclear burning portion of the initial mass function.

To connect the luminous and non-luminous parts to the halo init.al mass function, a single power law relation has been assumed. The justification for this assumption is that the physics which affects the lower mass limit for nuclear burning is independent of the physics which governs gravitational collapse and it would be a considerable coincidence if these two mass scales coincided. Nuclear burning depends on the fine structure constant, α, and the strength and range of strong interactions while the physics of gravitational collapse depends on α and the gravitational constant, G. Since the assumption that the halo initial mass function is a single power law is the strongest assumption in this manuscript, we shall return to this subject to present other supporting evidence and discuss the substantial problems that must be overcome to seriously consider a radically different initial mass function, namely a halo of Jupiters with negligible mass in nuclear burning stars.

As we shall show, the mass-to-light ratio, M/L, of a halo is a function of the slope of the initial mass function, x, and the lowest mass condensation which forms gravitationally, m_{min}, also known as the Jeans mass. The initial mass function is defined by

$$\phi_m = Am^{-(1+x)} , \qquad (3)$$

where ϕ_m is the number of stars per unit mass per unit volume of the halo. In general, A and x will depend on the mass range considered. The total mass density in stars and Jupiters, ρ_m, is

$$\rho_m = \int_{m_{min}}^{m_G} m\ \phi_m\ dm , \qquad (4)$$

which, using eq. (3) may be found to be,

$$= \frac{A}{1-x} [m_G^{1-x} - m_{min}^{1-x}] \; . \tag{5}$$

Here, m_G is the mass of a giant which is taken to be $m_G \approx 0.75\ M_\odot$ and for the present argument, we neglect the small fraction of the mass contained in more massive objects.

Using the initial mass function, the luminosity density of the halo, ρ_L, may be seen to be,

$$\rho_L = \int_{m_o}^{m_G} L_m \, \phi_m \, dm + L_G \; . \tag{6}$$

For

$$L_m = c \; m^D \; , \tag{6a}$$

$$\rho_L = \frac{Ac}{D-x} [m_G^{D-x} - m_o^{D-x}] + L_G \; , \tag{7}$$

where L_m is the luminosity of a star of mass m, and c and D are constants chosen for a particular spectral band. The lower limit of integration, m_o, in eq.(6), the lower limit for nuclear burning, has been taken to be $m_o \simeq 0.08\ M_\odot$ (25). The quantity, L_G, is the light due to giants. Since observational constraints are available in the I and K Johnson spectral bands for the halo of the edge-on spiral galaxy NGC 4565 we shall evaluate ρ_L in these bands. The data of Gunn and Tinsley (26) in the range 0.08 $M_\odot$ to 0.8 $M_\odot$ have been fit with the power law in eq.(6a). For the luminosity in the I band, $L_{m,I}$, $c = 1.49\times10^{-3}$ and D = 2.71 and, correspondingly, for $L_{m,K}$, $c = 3.12\times10^{-2}$ and D = 2.11 where mass is expressed in solar units and in each spectral band, the luminosity equals unity for a zero magnitude star.

To express the contribution of giants to the surface brightness we have used the method described in Tinsley (27). Since Tinsley discussed a metal abundance Z = .01, we corrected the Tinsley models using the calculations of Sweigart and Gross (28). Fitting the later calculations (for $m = .7\ M_\odot$, Y = .30) for the change in main sequence lifetime as a function of Z, the correction to the lifetime was found to be $\propto \exp[28.6Z - .286]$, that is, increasing Z increased main sequence lifetimes. Also, it may be seen that this factor is equal to unity for Z = 0.01. For these calculations we have used $Z = 10^{-5}$, a value appropriate to halo stars. Lifetimes for smaller metal abundances are not changed appreciably.

To calculate M/L for the halo of NGC 4565, we shall use $M/L = \rho_m/\rho_L = \sigma_m/\sigma_L$, where σ_m and σ_L are the projected mass and luminosity density. It is necessary to evaluate the projected halo mass density in terms of the 21 cm rotational velocity 253 km/s (29) and the maximum extent of the halo, R_{max}. This may be seen to be

$$\sigma_m = \frac{v^2}{2\pi G}\frac{1}{r}\tan^{-1}\sqrt{\left(\frac{R_{max}}{r}\right)^2 - 1} \qquad (8)$$

at galactic radius r. The distance to NGC 4565 is unlikely to be larger than 24 Mpc, and since the rotation curve has been observed out to 11.6 ', R_{max} = 81 Kpc. Using eq.(8) and eq.(7), it may be seen that M/L for the halo is only a function of x and m_{min}.

We now turn to the observational data on the surface brightness of the halo of NGC 4565. Data taken with the annular scanning photometer (30) in the Kron I band has been discussed by Hegyi (31), see Figure 1. That data has been transformed to the Johnson system and expressed in solar units. A least squares fit to that data using the functional form $\sigma_L = a/r + b$ has been performed. (This functional form assumes that R_{max} is large compared to r so that the $\tan^{-1}$ function in eq. 8 reduces to $\pi/2$.) A 2σ lower limit to σ_m/σ_L expressed in solar units in the Johnson I band is

$$M/L_I > 60\ M_\odot/L_{\odot,I}\ . \qquad (9)$$

Observations in the K band have been made by Boughn, Saulson, and Seldner (32) using a chopping secondary. Their 2σ lower limit is

$$M/L_K > 38\ M_\odot/L_{\odot,K}\ . \qquad (10)$$

We shall now determine whether the available observational and theoretical constraints on x and m_{min} can accomodate the limits on M/L in eqs. (9) and (10). The strongest constraints on x, derived from the observation of spectral features (26) and the initial mass function in the solar neighborhood (33) require $x < 1$ at the 2σ level. Also there is no data in conflict with $x < 1$. Photometric data ranging from globular clusters to elliptical galaxies can be fit using the weaker constraints $x < 1.35$, by a single free parameter, the metal abundance (34,35).

Constraints on m_{min}, the smallest mass to collapse gravitationally (36,37,38), have a lower limit of $\geq 0.007\ M_\odot$. A more recent calculation (39) in which new reactions to form

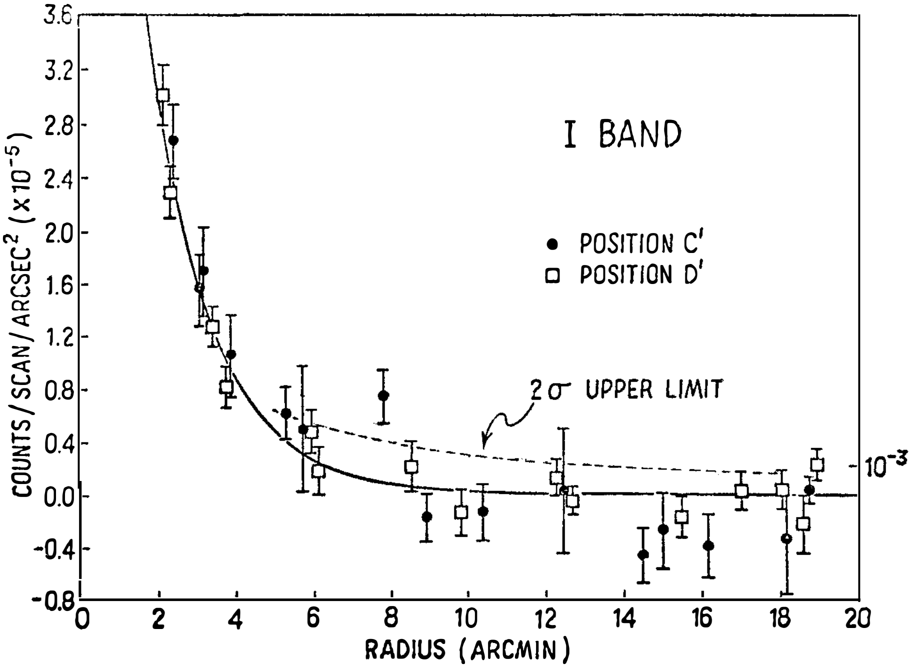

Figure 1. The measured surface brightness of the halo of NGC 4565 versus galactic radius. Positions C' and D' are two symmetric scanning positions. The curve fitted to the data is the de Vaucouleur's surface brightness law and the 2σ upper limit to the data is labelled. [1 count/scan/arc sec^2$\times 10^{-5}$ is 25.34 mag I_{Kron}.]

molecular hydrogen are considered, requires $m_{min} > 0.004\ M_\odot$. That result was found for optically thin clouds. An equally forceful position has been presented in which it is argued that the first objects to form have $m_{min} \geq 1500\ M_\odot$.

If we choose $m_{min} = .004\ M_\odot$ and find x to satisfy the I and K band NGC 4565 observations, we find x > 1.6 and 1.7 respectively. On the other hand, if we choose $x \leq 1$ and try to find the allowed range for m_{min}, we find no solution. It is not possible to put enough mass in the halo for this x without violating the surface brightness observations. For x = 1.35, we find $m_{min} < 2\times10^{-4}$ at least a factor of twenty below the calculated lower limit on m_{min}. These are the problems if one chooses to consider a single power law initial mass function and a halo of stars and/or Jupiters.

There are some observations which have a bearing on our assumption of whether the initial mass function is a single power law below the nuclear burning cutoff. Probst and O'Connell (41) argue that the initial mass function in the solar neighborhood does not even rise as steeply as a single power law for stellar masses less than 0.1 $M_\odot$. Instead the slope turns over, meaning that there is little mass contained in stars with $m < 0.1\ M_\odot$. Since these results are based on stars with solar metal abundance, the conclusions are strengthened for stars which have lower metal abundances and which cannot cool as effectively.

Though we have argued that it seems reasonable to use a power law for the slope of the initial mass near 0.08 $M_\odot$ and that any possible gravitational condensation of smaller mass would adhere to the same power law, let us now consider the possibility that only Jupiters formed. As a prototypical model, we shall consider the model presented at this conference by Professor Rees. In that model, a Jean's mass at recombination, 10^5-10^6 $M_\odot$, cools and forms a very thin disk of thickness equal to the Jean's length of a 10^{-3} $M_\odot$ condensation, that is, a Jupiter. Subsequently the disk fragments contributing 10^8-10^9 Jupiters to the formation of a halo of Jupiters.

There appear to be two large-scale instabilities which the disk must avoid if Jupiters are to form: the tendency of the disk to form a bar, and the instability of a cool disk to form massive condensations which are a significant fraction of the total disk mass (42). We shall disucss the second instability using the Toomre stability criterion.

The basic kinematic criterion for stability is that the time for a blob of material to orbit the disk, t_{orb}, should be longer than the time for a pressure wave or sound wave to cross the disk, t_s. Writing $t_{orb} \sim r/v$ and $t_s \sim r/c_s$, we have

$$t_{orb} > t_s \tag{11}$$

leading to

$$r/v > r/c_s \tag{12}$$

or

$$v < c_s \ . \tag{13}$$

This is the condition that, for stability, the orbital velocities be less than the individual particle velocities. Adding the dynamics, namely, in equilibrium, the following condition for circular motion must be satisfied,

$$v^2/r = GM/r^2 \ . \tag{14}$$

For a disk with mass per unit area, σ, $M \sim \pi\sigma r^2$, then substituting for M in eq. (14) and multiplying by r, we have

$$v^2 = \pi G\sigma r \ . \tag{15}$$

Substituting this result into eq. (13) leads to

$$\pi G\sigma r < c_s{}^2 \tag{16}$$

The speed of sound is $c_s{}^2 \sim KT/m_p$. Also, from the Jeans mass condition we have

$$GM_J/r_J \sim KT/m_p \ . \tag{17}$$

where M_J is the Jeans mass and r_J is the Jeans length. Substituting eq. (17) into eq. (16), it may be seen that

$$\pi G\sigma r < c_s{}^2 \sim GM_J/r_J \tag{18}$$

or

$$\pi\sigma r r_J < M_J \ . \tag{19}$$

If we write the thickness of the disk, t, in terms of the radius of the disk, r, then $t = \varepsilon r$. With $t \simeq r_J$ and $M \sim \pi\sigma r^2$, we have

$$\varepsilon M < M_J \ . \tag{20}$$

From the numbers required by the model, that is, dividing a 10^5 $M_\odot$ object into 10^{-3} $M_\odot$ objects or 10^8 Jupiters, it may be seen that the ratio t/r required for a disk of thickness equal to the Jeans length of a Jupiter is $\sim \sqrt{10^{-8}} = 10^{-4}$. Using this value for ε on the left hand side of eq. (20) yields ~ 10 $M_\odot$, while the desired Jeans mass is 10^{-3} $M_\odot$. The inequality is not satisfied by a factor of 10^4. That is, such thin disks are unstable and form ~ 10 $M_\odot$ objects, not Jupiters. An alternative interpretation is that a disk which is hot enough for stability is too hot to allow low mass gravitational condensations to develop.

The halo cannot be made of stars which have an initial mass greater than 2 $M_\odot$. Such stars either evolve to white dwarfs with mass ≈ 1.4 $M_\odot$ (43) or to neutron stars which also, coincidently, have masses ≈ 1.4 $M_\odot$. Taylor and Weisberg (44) have found two neutron stars with masses of 1.4 $M_\odot$ to within 1% and all other neutron star mass determinations are consistent with 1.4 $M_\odot$. Consequently, any star with initial mass greater than 2 $M_\odot$ must lose 40 per cent of its mass during evolution. The ejected mass cannot be hot because of previous arguments and it cannot cool and fall in the disk because there is too much mass to be contained. Also, since a significant fraction of the mass of the evolved stars, $\gtrsim$ 10%, might be expected to be converted into helium and metals during evolution, problems similar to those raised by metallic halos could be present.

Though black holes do not have a well defined baryon number, we shall briefly consider them because if halos are not baryonic, they are evidently either composed of black holes or some weakly or very weakly interacting particles (see review by Joel Primack in this volume).

It appears unlikely that many black holes in the mass range 1-50 $M_\odot$ formed in the halo. Stars in this mass range eject a considerable fraction of their mass. Unless the black holes can accrete virtually all their ejecta, problems similar to those with metallic halos arise. Black holes which are more massive than 100 $M_\odot$ appear to be excluded by new observations (45), though they need to be confirmed. Thus, halos could be composed of black holes in the mass range ~50-100 $M_\odot$ (46) or they could be primordial.

Arguing by eliminating specific baryonic forms of matter is not the most persuasive way to argue that halos are not baryonic, but, unfortunately, we are unable to present a forceful positive argument eliminating baryons directly. In this context, it is worth considering the constraints that primordial nucleosynthesis places on baryonic halos, though we admit that there are strong assumptions implicit in the nucleosynthesis calculations.

In this context, we shall take the simplest point of view, namely, that all the dark matter in halos and rich clusters is either all baryonic, or not baryonic and see which conclusion, if any, the nuclear abundances favor.

A lower limit to the mass fraction of the closure density in baryons, Ω_b, may be obtained from the luminous matter in galaxies and could be as low as .001. The thermal X-ray fluxes from clusters of galaxies yield higher baryon abundances but do not exclude $\Omega_b \sim .001$. On the other hand if all the dark matter were baryonic, the mass content of halos and rich clusters would require a lower limit for the baryonic abundances to be, $\Omega_b \gtrsim 0.1$.

The deuterium abundance of $\sim 1\times10^{-5}$ by mass does not favor either high or low baryon abundances. There are problems with both ranges. However, the deuterium abundance may not be well known (see Audouze this volume). The He^4 abundance is presently observed to be in the range Y ~ .22-.25 (47). Since an observed helium abundance is an upper limit on the primordial abundance, and since $\Omega_b \gtrsim .1$ requires Y $\gtrsim$ .26, the helium observations favor a low baryon abundance. The observed Li^7 abundance (48) is consistent with two abundance ranges, $\Omega_b \sim .001-.003$ and $\Omega_b \sim .01-.02$. It appears inconsistent with $\Omega_b \gtrsim .1$. Taken together, the abundance data favors a low baryon abundance (49). A key test of the cosmological baryon abundance will be a new measurement of the primordial helium abundance which is independent of the possible systematic effects in the present spectroscopic measurements.

I would like to thank G. William Ford, Martin Rees, Alar Toomre and Scott Tremaine for useful discussions.

REFERENCES

1. Hohl, F. 1977, NASA TR R-343.

2. Hohl, F. 1975, in IAU Symposium No. 69, "Dynamics of Stellar Systems, ed. A. Hayli (Dordrecht, Neth: Reidel), pp. 349.

3. Kalnajs, A.J. 1972, Ap. J. 175, pp. 63.

4. Ostriker, J.P and Peebles, P.J.E. 1973, Ap.J. 186, pp. 467.

5. Rogstad, D.H. and Shostak, G.S. 1972, Ap. J. 176, pp. 315.

6. Roberts, M.S. and Rots, A.H. 1973, Astr. Ap. 26, pp. 483.

7. Haschick, A.D. and Burke, B.F. 1975, Ap. J. (Letters) 200, pp. L137.

8. Roberts, M.S. 1975 in IAU Symposium No. 69, "Dynamics of Stellar Systems, ed. A. Hayli (Dordrecht, Neth: Reidel), pp. 331.

9. Sancisi, R. 1977, IAU Symposium No. 77, "Dynamics of Stellar Systems, ed. A. Hayli (Dordrecht, Neth: Reidel).

10. Krumm, N. and Salpeter, E.E. 1979, A.J. 84, pp. 1138.

11. Rubin, V.C., Ford, Jr., W.K., and Thonnard, N. 1978, Ap. J. (Letters) 225, pp. L107.

12. Turner, E.L. 1976, Ap. J. 208, pp. 304.

13. Peterson, S.D. 1979, Ap. J. 232, pp. 20.

14. Rivolo, A.R. and Yahil, A. 1981, Ap. J. 251, pp. 477.

15. Saar, E.M. 1978 in IAU Symposium 84, "The Large-Scale Characteristics of the Galaxy", ed. W.B. Burton, p. 513.

16. Tubbs, A.D. and Sanders, R.H. 1979, Ap. J. 230, pp. 736.

17. Monet, D.G., Richstone, D.O. and Schechter, P.L. 1981, Ap. J. 245, pp. 454.

18. Van der Kruit, P.C. 1981, Ast. Ap. 99, pp. 298.

19. Rohlfs, K. 1982, Astr. Ap. 105, pp. 296.

20. Hegyi, D.J. and Olive, K.A., to be published 1983, Physics Letters.

21. Faber, S.M. and Gallagher, J.S. 1979, Ann. Ref. Astr. Ap. 17, pp. 135.

22. Johnson, V.J. 1960, "A Compendium of the Properties of Materials at Low Temperature (Phase I)", U.S. Air Force.

23. Hollenbach, D. and Salpeter, E.E. 1971, Ap. J. 163, pp. 155.

24. Dekel, A. and Shaham, J. 1979, Astro. Ap. 74, pp. 186.

25. Straka, W.C. 1971, Ap. J. 165, pp. 109.

26. Tinsley, B.M. and Gunn, J.E. 1976, Ap. J. 203, pp. 52.

27. Tinsley, B.M. 1976, Ap. J. 203, pp. 63.

28. Sweigart, A.V. and Gross, P.G. 1978, Ap. J. Suppl. 36, pp. 405.

29. Krumm, N. and Salpeter, E.E. 1979, A.J. 84, pp. 1138.

30. Hegyi, D.J. and Gerber, G.L. 1977, Ap. J. (Letters) 218, L7.

31. Hegyi, D.J. in Proceedings of the Moriond Astrophysics Meeting (ed. J. Andouze, P. Crane, T. Gaisser, D. Hegyi, and J. Tran Thranh Van) Frontiers, 1981, pp. 321.

32. Boughn, S.P., Saulson, P.R. and Seldner, M. 1981, Ap. J. (Letters) 250, pp. L15.

33. Miller, G.E. and Scalo, J.M. 1979, Ap. J. Suppl. 41, pp. 513.

34. Aaronson, M., Cohen, J.G., Mould, J. and Malkan, M. 1978, Ap. J. 223, pp. 824.

35. Frogel, J.A., Persson, S.E. and Cohen, J.G. 1980, Ap. J. 240, pp. 785.

36. Low, C. and Lynden-Bell, D. 1976, M.N.R.A.S. 176, pp. 367.

37. Rees, M.J. 1976, M.N.R.A.S. 176, pp. 483.

38. Silk, J. 1982, Ap. J. 256, pp. 514.

39. Palla, F., Salpeter, E.E., and Stahler, S.W. (preprint).

40. Tohline, J.F. 1980, Ap. J. 239, pp. 417.

41. Probst, R.G. and O'Connell, R.W. 1982, Ap. J. (Letters) 252, L69.

42. Toomre, A. 1964, Ap. J. 139, pp. 1217.

43. Chandrasekhar, S. 1935, M.N.R.A.S. 95, pp. 207.

44. Taylor, J.H. and Weisberg, J.M. 1982, Ap. J. 253, pp. 908.

45. Lin, D.N.C. and Faber, S.M. 1983 (preprint).

46. Carr, B.J., Bond, J.R. and Arnett, W.D. 1983 (preprint).

47. Pagel, B. 1982, Phil. Trans. of R.S. London 307, pp. 19.

48. Spitz, M. and Spitz, F. 1982, Nature 297, pp. 483.

49. Olive, K.A., Schramm, D.N., Steigman, G., Turner, M.S., Yang, J. 1981, Ap. J. 246, pp. 557.